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A novel method to analyze trends of extreme precipitation distribution- A case study over the Arctic regions of Canada

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ABSTRACT

Climate change is thought to be changing precipitation regimes in northern Canada, particularly in terms of magnitude and the frequency of extreme events. Given the large geographic size of the Arctic and the relative sparsity of meteorological stations with historical weather observations, characterizing large scale climate trends remains challenging. This paper analyzes the trend of extreme precipitation over the Arctic regions of Canada through the analysis of a gridded (10km x 10km) precipitation dataset to calculate the annual maximum daily precipitation between 1950-2010. However, the different grid points in any derived gridded datasets have spatial auto-correlations which can potentially induce bias in the trend estimation, when considering all the grid points. To mitigate these problems, we proposed a novel spatial-pooling method which creates a spatially decorrelated variable distribution considering the effective correlation radius of the variable. Furthermore, we analyze the spatially decorrelated precipitation time-series using the extreme value theory in the context of long-term low-frequency variability. The trend pattern suggests increasing frequency and variability of extreme precipitation over the Southern Arctic regions. Analysis of extreme precipitation over the northern Arctic was inconclusive. Our analysis emphasizes the need for robust trend estimation methods in the arctic regions where data uncertainty is very high due to low station density. Standard trend analysis of the gridded observation data may lead to false positive trends.

1. Introduction:

Extreme precipitation events are one of the major influencing factors in the design, analysis, and operation of various water resource infrastructure. Climate change has potential to alter precipitation patterns, intensities, and extremes. Various global climate modelling studies indicate that global warming can have more prominent effects on extreme precipitation than on mean precipitation (Mailhot et al., 2007; Bates et al., 2008).

The Arctic regions of Canada are warming much faster than the lower latitudes through a process referred as Arctic Amplification (AA) (Francis and Vavrus, 2012; Serreze and Barry 2014; Overland et al. 2015). Glisan and Gutowski (2014) indicate that the regions of the Arctic which have low-level convergence of moisture are prone to extreme precipitation events. Furthermore, the recent increase of occurrences of cyclonic activities can possibly add to the moisture content of the atmospheric column and which in turn may lead to stronger extremes such as extreme precipitation scales to total column moisture content (IPCC, 2013).

Thus, in the context of present and future possible climate changes, it is important to study the change characteristics of extreme precipitation over the Arctic regions of Canada. However, the direct application of analytical methods developed and used where station density is high are likely to perform poorly in areas where the station density is much lower. Careful consideration of both process spatial dependence and induced dependence through interpolation models is needed. Accordingly, the objectives of our study are as follows:

i. To provide a novel method to analyze the trend over gridded datasets where nearby grid points can be highly correlated.
ii. Analyze the trends of spatial mean and standard deviation of annual mean precipitation over Northern and Southern Arctic regions of Canada.
iii. Analyze the spatial variation of trends of extreme precipitation.
iv. Analyze trends of return period level for extreme precipitation within an extreme value analysis framework.

2. Methods and Data:

The Pacific Climate Impacts Consortium (PCIC) NRCANmet gridded (10km x 10km) precipitation dataset (Hopkinson et. al., 2011; Hutchinson et. al., 2009) were obtained for all of Canada; years 1950-2010. The NRCANmet observational dataset was produced by Natural Resources Canada (NRCan). Gridding was accomplished with the Australian National University Spline (ANUSPLIN) implementation of the tri-variate thin plate splines interpolation method (Hutchinson et al., 2009) with latitude, longitude and elevation as predictors. Furthermore, a Canada ecozone shapefile from the CGDI National Frameworks Data was used to define the boundaries of the Northern and Sothern Arctic regions.

The analysis methodologies consisted of a sequence of steps. First, the annual maximum precipitation is calculated for each of the grid points for the duration 1950-2010 using the gridded precipitation dataset. Secondly, the precipitation grids belonging to each of the eco-regions are identified using ecozone boundaries. The semi-variogram of the median extreme precipitation for each of the eco-regions is then calculated and used to determine the correlation range of extreme precipitation within each ecozone. Hexagonal grids with size (center to center distance) equal to the correlation range are then generated. The hexagonal grid ensures the equal distance of neighbors in each direction.

The precipitation data are then mapped to the center of the grid using a nearest neighbor approach. This procedure finally produces the hexagonally gridded de-correlated extreme precipitation time-series for each of the eco-regions. The temporal trend of spatial mean and spatial standard deviation are estimated using the mean and standard deviations of hexagonal grid centres over each of the eco-regions. In addition, the trends of individual hexagonal grid points are also calculated. Finally, return period precipitation levels (RL) are estimated with 30-year moving windows using Generalized Extreme Value (GEV) distributions fitted on each of these windows. Then, we estimate the return period precipitation levels from the GEV distribution. The trends of 30-years RL and 100-years RL are analyzed in this paper.

2.1 Study Area

The comparison focused on in this paper is the two arctic ecozones of Canada. The Northern Arctic Ecozone is the coldest and driest landscape in the Arctic which comprises the non-mountainous portions of the Arctic Islands as well as the northernmost areas of Quebec. The mean annual precipitation is very low, ranging from 10–20 cm. The Southern Arctic Ecozone covers much of the northern mainland of Canada, from the the Yukon Territory to northern Quebec. An annual mean precipitation of 20–50 cm is observed here.

3. Results

Figure 1 presents the eco-zone boundaries of the Northern and Southern Arctic overlaid with the hexagonal grid which are constructed as part of this study and the Environmental Canada meteorological stations within the study zones. In the inset the boundaries of all the eco-zones are shown and the Northern Arctic and Southern Arctic are highlighted in yellow. The hexagonal mesh over each of the ecoregions with sizes equal to the range parameters of the corresponding variogram. The hexagonal grids are clipped at the boundary of the region and the centers are recalculated as the centroid of the clipped region. This ensures the mapped nearby grid points are taken from the ecozone itself. Notice the sparsity of the stations in these areas. This low density can be attributed to lower population and economic activities in this region, but is in contrast to the anticipated need for detailed weather data to track climatic changes in the North.

The empirical variogram models (Figure 2) give the estimated range parameters of around 32,000 km for Northern Arctic and around 286 km for Southern Arctic region. The sparse station density on the Northern Arctic region likely contributes to the larger range of this region. Figure 3 and 4 presents the trends of spatial-mean of annual extreme precipitation over Northern Arctic and Southern Arctic regions using both the grid points and sub-samples. For the Northern Arctic region, the trend computed from all the grid points is significant at 99% confidence level and has median estimate of 0.03 mm/year. Considering around 10 mm of intercept this trend indicates around 24% increase of precipitation in 60 years. However, the sub-sampling method reveals no significant trend. The low station density in this region can lead to this type of contrasting trend estimation when we consider the spatial correlation into the trend estimation method. The Southern Arctic region also has 99% confidence level trend with median estimate of 0.05 mm/year when considering all the grid points (Figure 3). Like the Northern Arctic, this trend indicates an increase of 23% during the studied 60-year period. The higher station density in this region enables us to put greater confidence in this estimate. This is also reflected in sub-sampling estimate of precipitation which had also detected a significant trend.

The trends of spatial-standard deviation of annual extreme precipitation for Northern Arctic region the trend is not significant at 99% confidence level and has median estimate of 0.02 mm/year (Figure 5). The sub-sample estimation of standard deviation trend is also not significant and is almost close to zero. The Southern Arctic region was significant at 99% confidence level trend with median estimate of 0.05 mm/year considering all the grid points (Figure 6).

This is also consistent with the sub-sample estimation of trend of spatial standard deviation. The trends of annual maximum precipitation over the individual grids is given in Figure 7. Notice, the Southern Arctic only has few grid points with significant trends. The spatial distribution of trend shows an overall increase of extreme precipitation.

Thirty-year return period extreme precipitation over the individual hexagonal grids show some significant spatial trends. This indicates more severe extreme events at this level. Also, notice there are a few grid points with significant decreasing trend indicating less severe extreme events at this RP level. This further gives a notion of a stable unchanged moisture balance over the region where increase precipitation in one region will result into decrease in other regions. For the 100-year return period extreme precipitation over the individual hexagonal grids, there was a change of significance level of few grid points in contrast to the 30-years return period plots. This signifies increased extreme precipitation on the grid points where confidence level changed from low to high. Furthermore, the grid points where confidence levels changed from high to low possibly indicates a convergence of the distribution for higher return period levels. Overall, Figure 8 and 9 indicate an increase in severity of extreme events.

Comparisons of station level annual maximum precipitation against the same from grid cell are reasonably good to comment on statistical properties of precipitation on the grid cell where a number of stations are present. For example, Figure 10 presents the two stations in studied zones where the magnitude of precipitation are in good agreement with the nearby grid points with correlation 0.58 and 0.93 respectively for Northern and Southern Arctic and can be compared well in terms of trend. However, we have reservation in commenting on the trend of grid points where few or no stations are present in the vicinity,

Northern and Southern Arctic Zones with the hexagonal grids and Meteorological stations

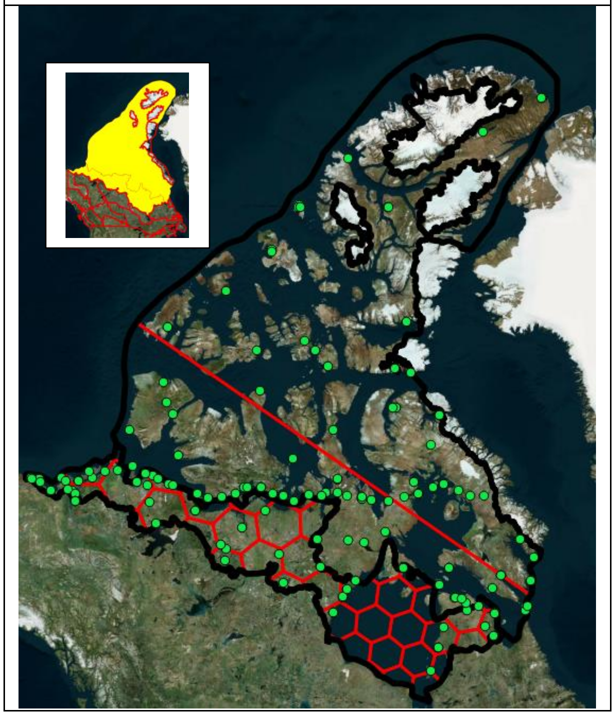
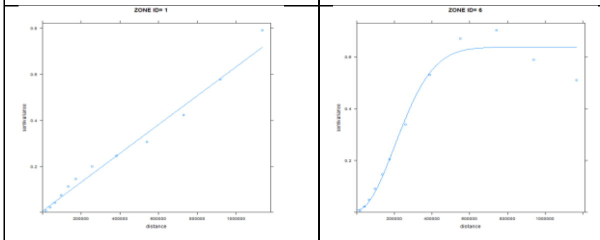


Figure 1: The boundaries of the Northern and Southern Arctic zones overlaid with the hexagonal grids and meteorological stations.



a) Northern Arctic

b) Southern Arctic

Figure 2: Semi-variogram and empirical variogram model of annual extreme precipitation over (a) Northern Arctic and (b) Southern Arctic regions

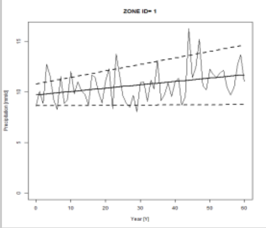
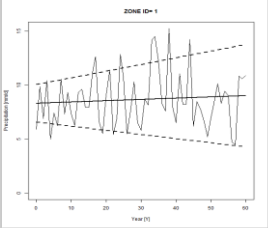
a) Full Gridded	**b) Sub-sampled**
	

Figure 3: Trend in spatial-mean of annual extreme precipitation over Northern Arctic for (a) Full Gridded data and (b) Sub-samples

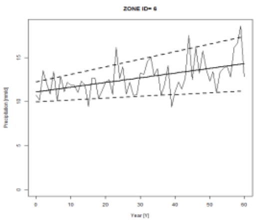
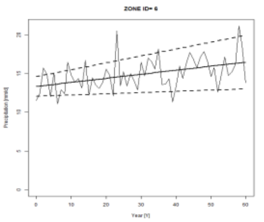
a) Full Gridded	**b) Sub-sampled**
	

Figure 4: Trend in spatial-mean of annual extreme precipitation over Southern Arctic for (a) Full Gridded data and (b) Sub-samples

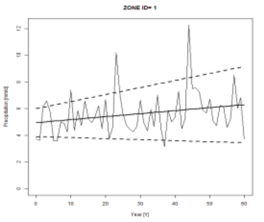
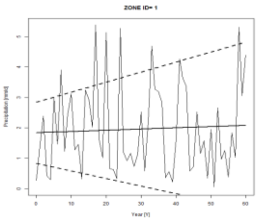
a) Full Gridded	**b) Sub-sampled**
	

Figure 5: Trend in spatial-standard deviation of annual extreme precipitation over Northern Arctic for (a) Full Gridded data and (b) Sub-samples

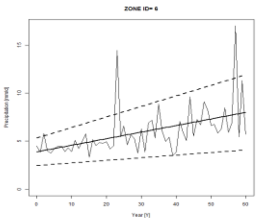
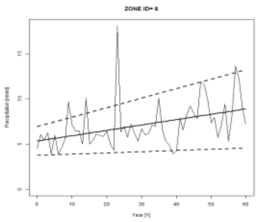
a) Full Gridded	**b) Sub-sampled**
	

Figure 6: Trend in spatial-standard deviation of annual extreme precipitation over Southern Arctic for (a) Full Gridded data and (b) Sub-samples

Trend in annual maximum precipitation

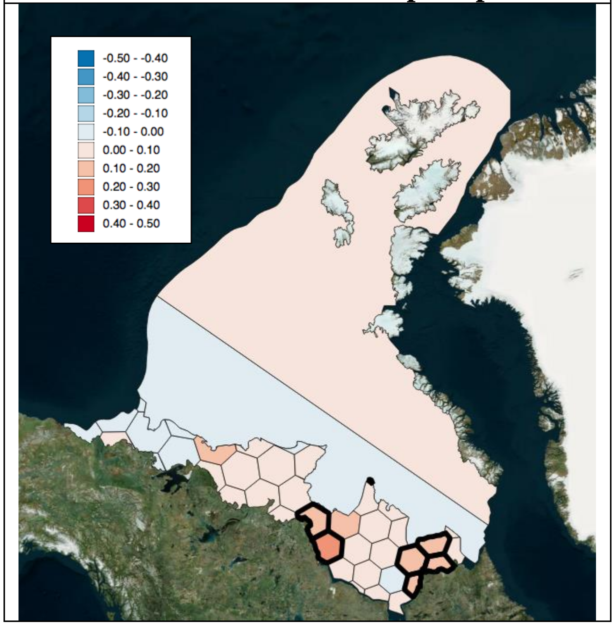


Figure 7: The trend of annual maximum precipitation on individual grid points. The grid points with 99% confidence level trends are highlighted with bold boundaries.

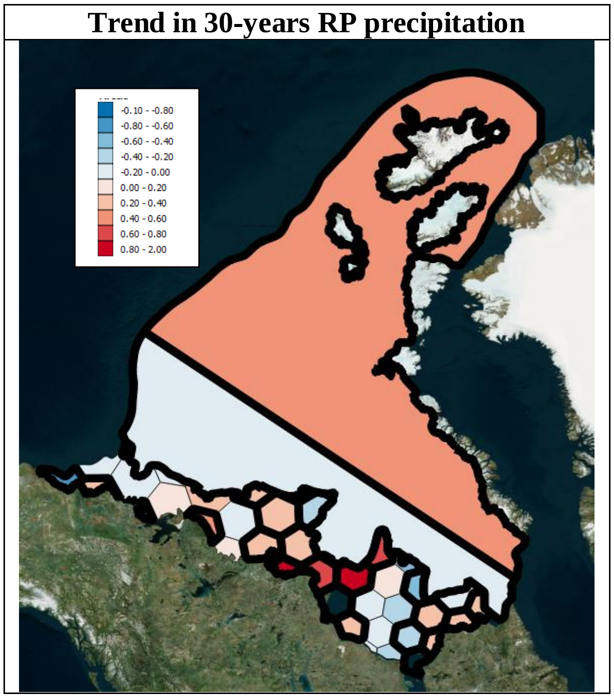

Trend in 30-years RP precipitation

Figure 8: The trend of 30-years return period precipitation level estimated using moving window approach. The grid points with 99% confidence level trends are highlighted with bold boundaries.

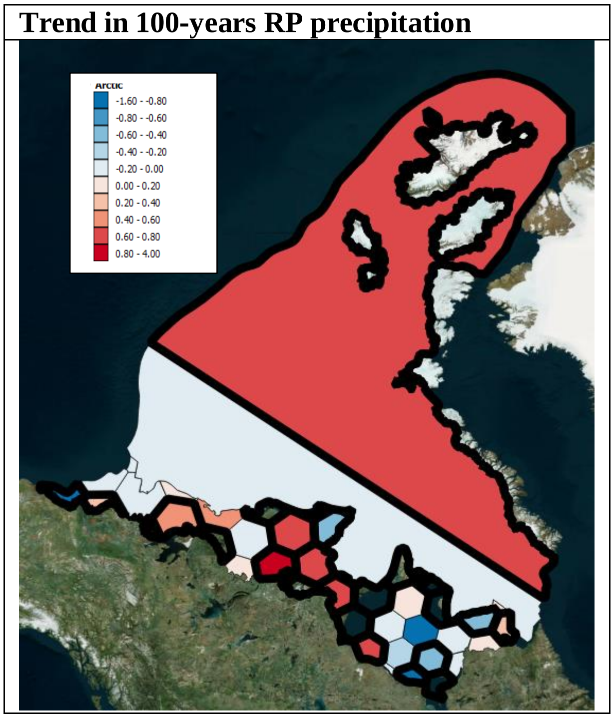
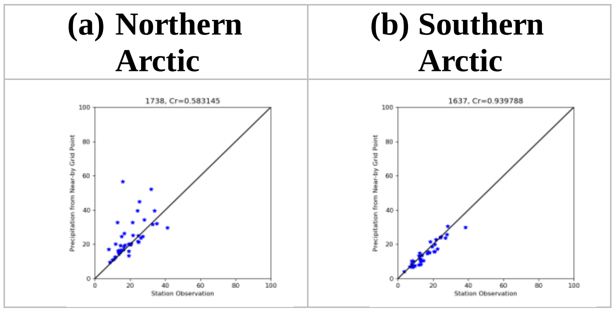

Trend in 100-years RP precipitation

Figure 9: The trend of 100-years return period precipitation level estimated using moving window approach. The grid points with 99% confidence level trends are highlighted with bold boundaries.


(a) Northern Arctic

(b) Southern Arctic

Figure 10: Comparison of station level annual maximum of grid level annual maximum for two stations in Northern and Southern Arctic regions.

4. Conclusion

In summary, the conclusions of this study are as follows;

i. This study indicates the necessity of considering spatial correlation of extreme precipitation when analyzing trend. This consideration is extremely important for the regions where station density is low and the gridded dataset presents a false sense of data coverage. We can qualitatively draw an inverse relationship between the station density and the range parameter of the semi-variogram.

ii. The trend in Southern Arctic regions is consistent with the modeling studies indicating increase in Arctic extreme precipitation (Bintaja R. et. al., 2017). However, the trend in Northern Arctic is in contrast with the trends computed considering all the grid points. Uncertainties of the trend estimation can be attributed to the low station density in that region.

iii. The trend in spatial standard-deviation indicates the possible changes of local drivers such as; landcover and/or disturbances during the study period over the Southern Arctic region.

We have produced an unbiased spatial-time series of annual maximum precipitation for Northern and Southern Arctic regions and detected trends in the Southern Arctic at eco-zone level. However, the sparse station density in the region prevented us from drawing major conclusion regarding the trends at the local level. Our analysis is effective when we are trying to analyze the eco-zone scale, however, this analysis cannot capture fine-scale structure of precipitation. Linkage to both instrumented field plot data and additional climate modelling studies might provide further confidence in the findings presented here.

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